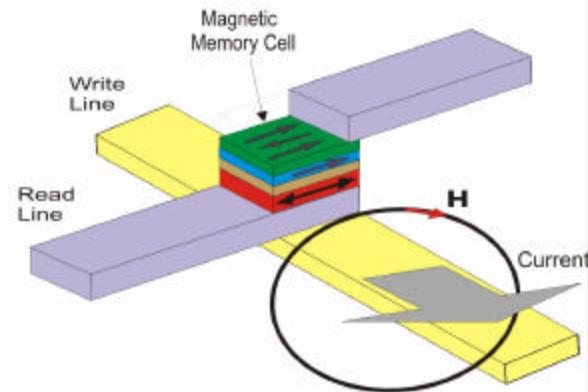
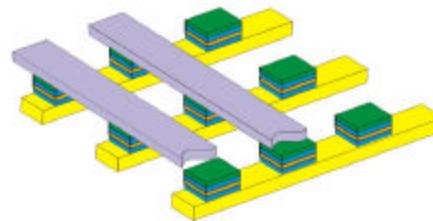


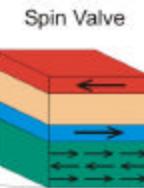
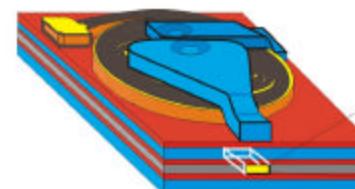
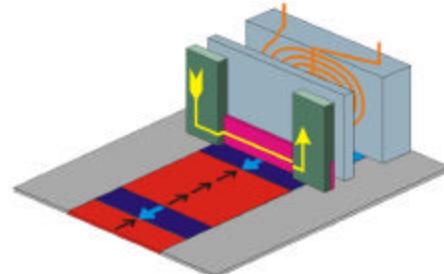
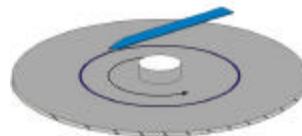
## Magnetic Technologies in Computers

### Memory

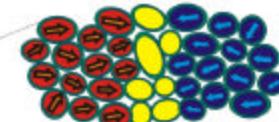
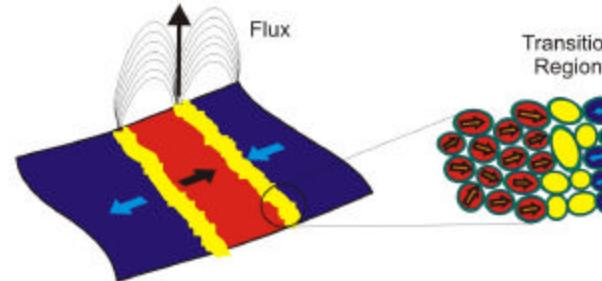


### Storage

### Head



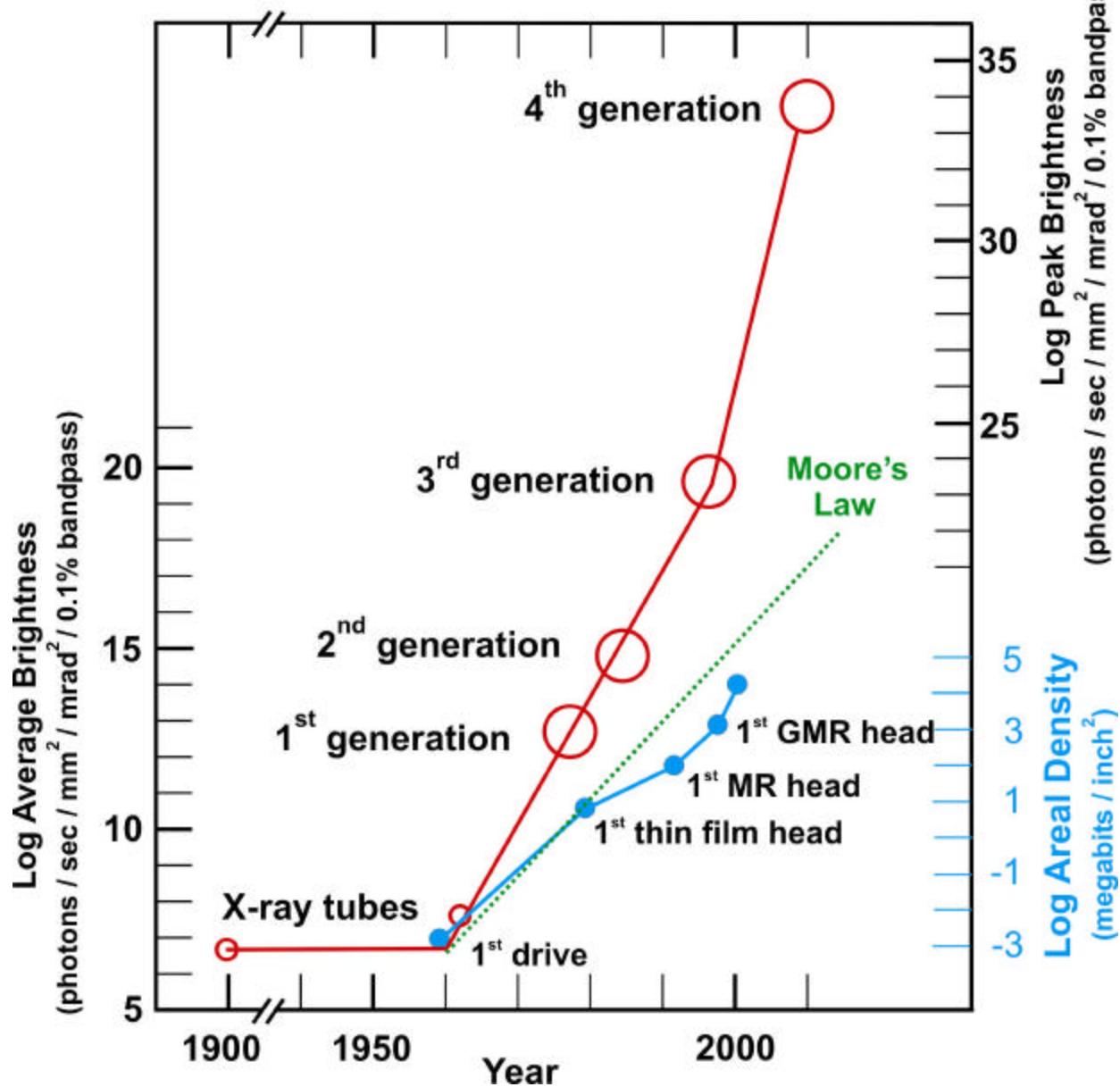
### Disk



Present: Size  $> 0.1 \mu\text{m}$ , Speed  $> 1 \text{ nsec}$   
Future: Size  $< 0.1 \mu\text{m}$ , Speed  $< 1 \text{ nsec}$

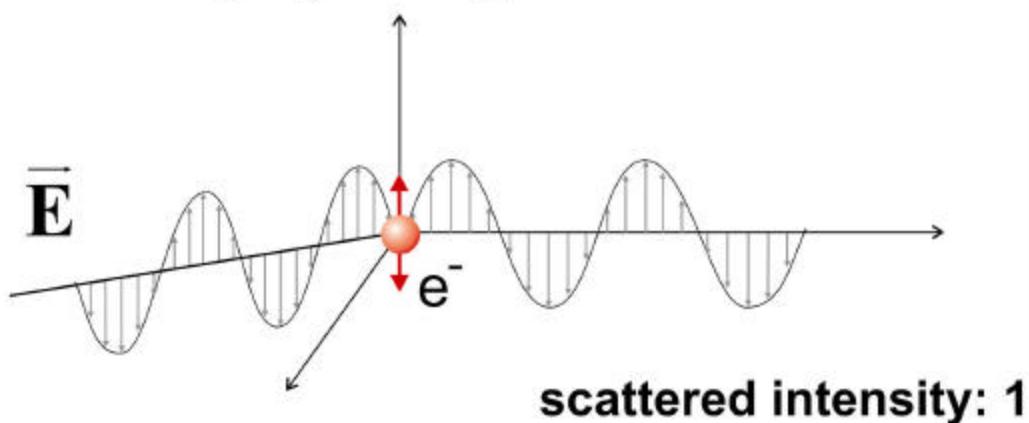
→ Ultrafast Nanoscale Dynamics

## Growth of X-Ray Brightness and Magnetic Storage Density



# X-Ray Scattering by Electrons and Spins

## Scattering by charge



Lorentz:

$$m \mathbf{a} = -e \mathbf{E} - e \mathbf{v} \times \mathbf{B}$$

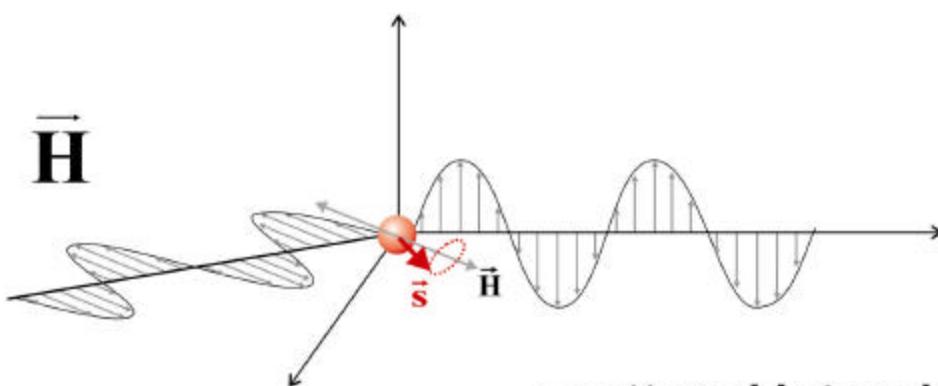
scattered intensity:

$$I_{\text{scat}} \sim | \mathbf{a} |^2$$

1<sup>st</sup> term, charge:

$$| \mathbf{a} |^2 = (e^2/m^2) E^2$$

## Scattering by spin



2<sup>nd</sup> term, spin:

$$| \mathbf{a} |^2 = (hv/mc^2)^2 (e^2/m^2) E^2$$

$$\mathbf{B} = (\mathbf{k}_o \times \mathbf{E}) / c$$

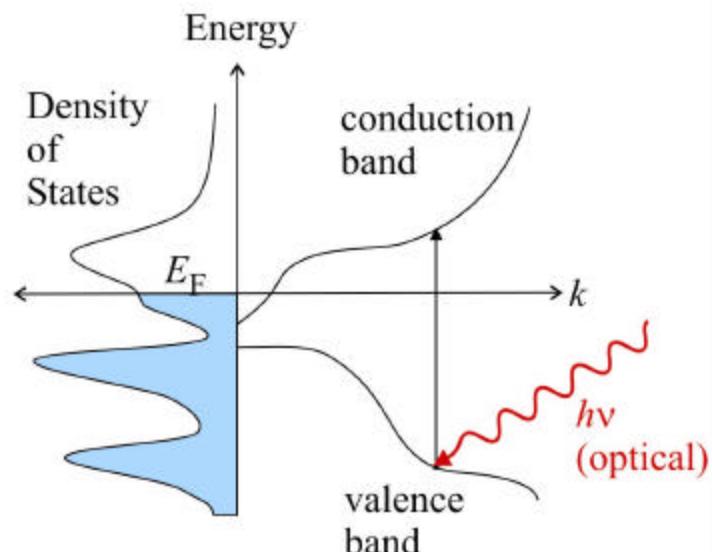
momentum conservation:  
 $v m = h v / c$

$$\text{scattered intensity: } (hv/mc^2)^2$$

$$mc^2 \sim 0.5 \text{ MeV}$$

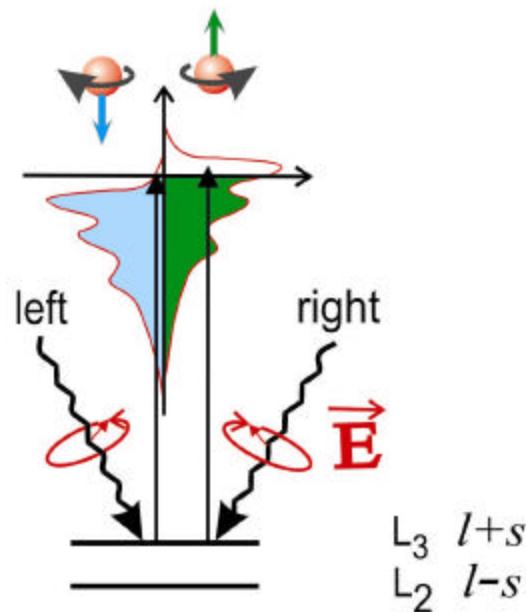
# Why X-Rays?

Faraday and Kerr effect



Magneto-optical response:  
weak,  $k$ -dependent

X-ray Magnetic Dichroism



X-ray response:  
strong,  $k$ -integrated quantities  
number of holes, spin moment, orbital moment

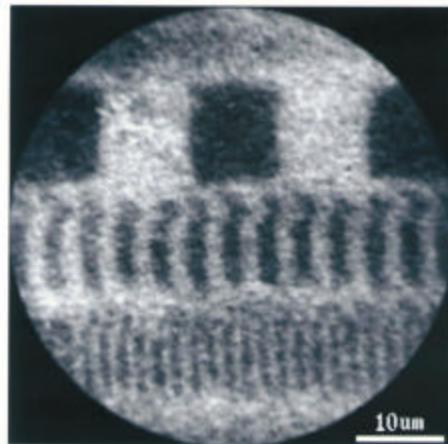
Core level binding energies give:  
**Element specificity**  
**Chemical state specificity**

## Magnetic Imaging with X-Rays

### Ferromagnets

#### X-Ray Magnetic **Circular** Dichroism

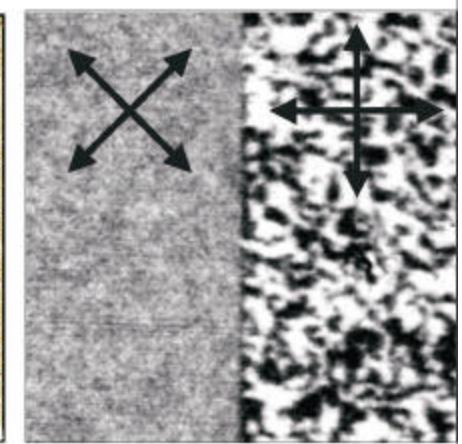
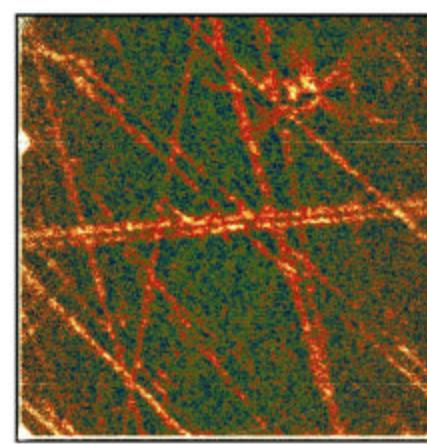
Stöhr *et al.*, Science **259**, 658 (1993)



### Antiferromagnets

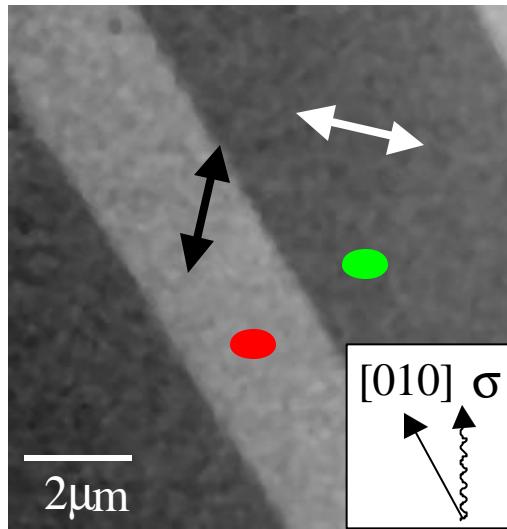
#### X-Ray Magnetic **Linear** Dichroism

Stöhr *et al.*, Phys. Rev. Lett. **83**, 1862 (1999)  
Scholl *et al.*, Science **287**, 1014 (2000)

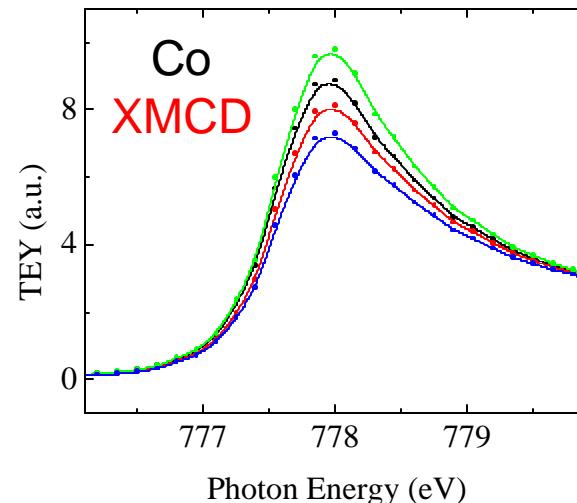
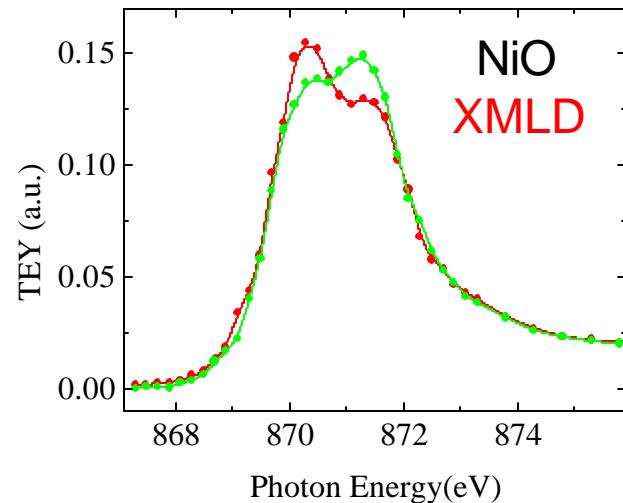
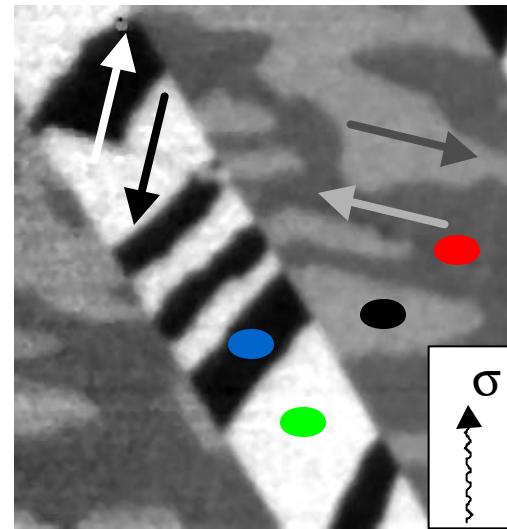


# Spectromicroscopy of Ferromagnets and Antiferromagnets

AFM domain  
structure at  
surface of **NiO**  
substrate



FM domain  
structure in  
thin **Co film on**  
**NiO** substrate



H. Ohldag, A. Scholl *et al.*, Phys. Rev. Lett. 86(13), 2878 (2001).

# X-Ray Dichroism in Absorption and Scattering

## Absorption

Sample density  $\rho$

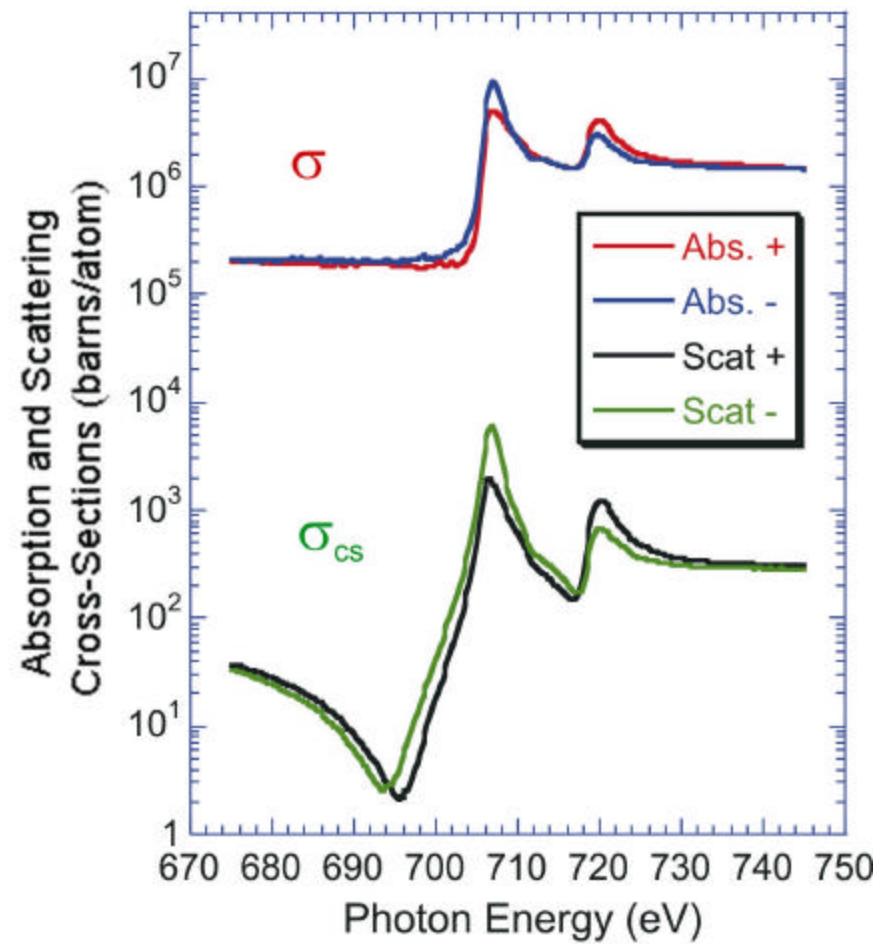
$$I_t = I_0 e^{-\sigma \rho}$$

$$\sigma = C f_2 / h\nu$$

## Resonant Elastic Scattering

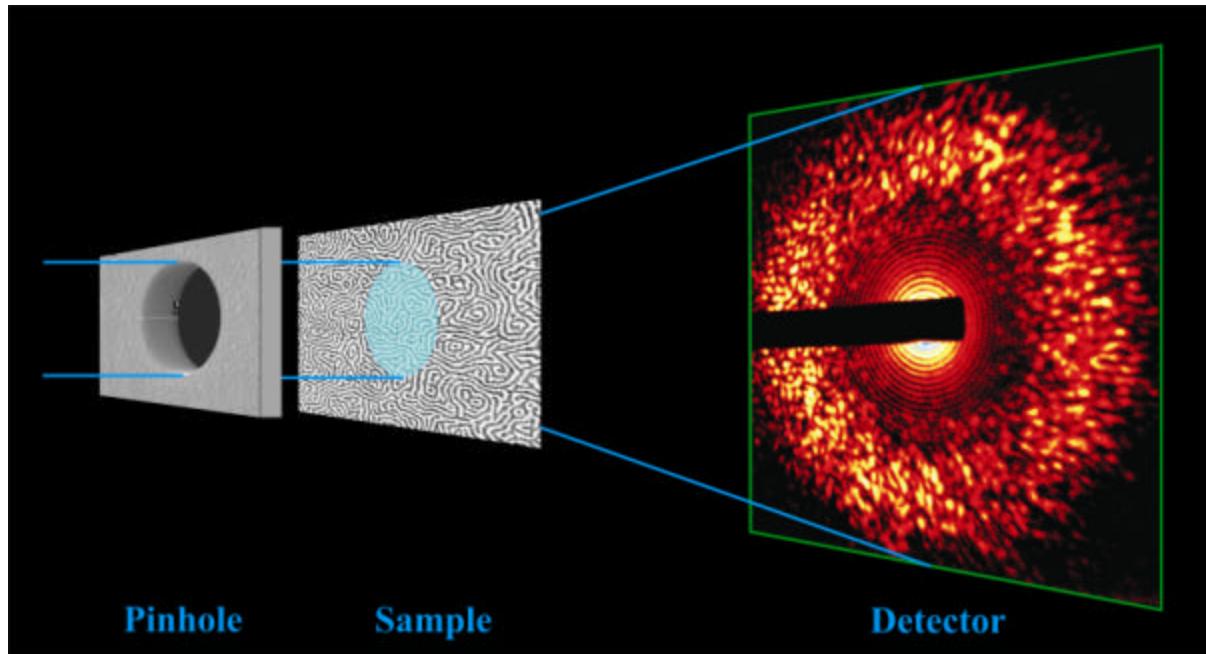
$$I_{sc} = I_0 \frac{\sigma_{cs}}{\sigma}$$

$$\sigma_{cs} = c |f_1 + i f_2|^2$$

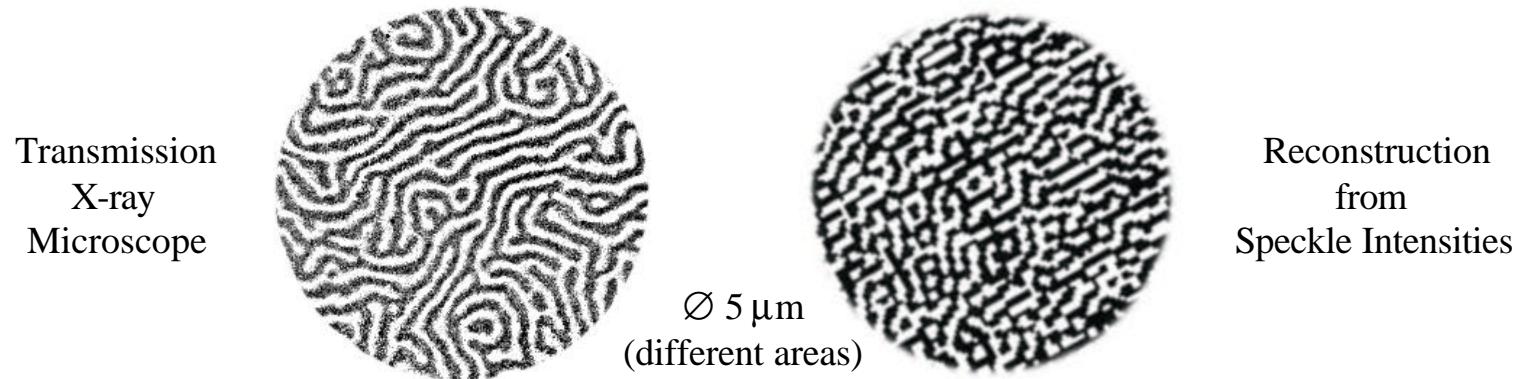


Kortright and Kim, Phys. Rev. B **62**, 12216 (2000)

# Imaging by Coherent X-Ray Diffraction



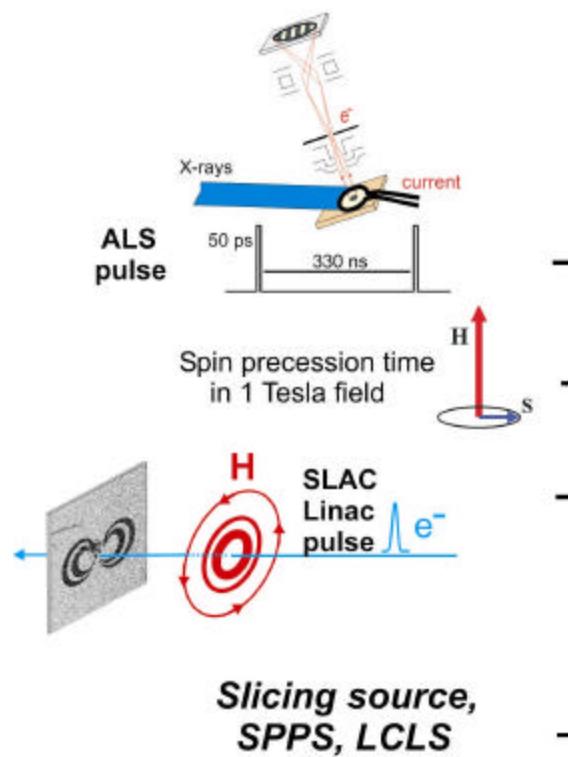
Phase problem can be solved by “oversampling” speckle image



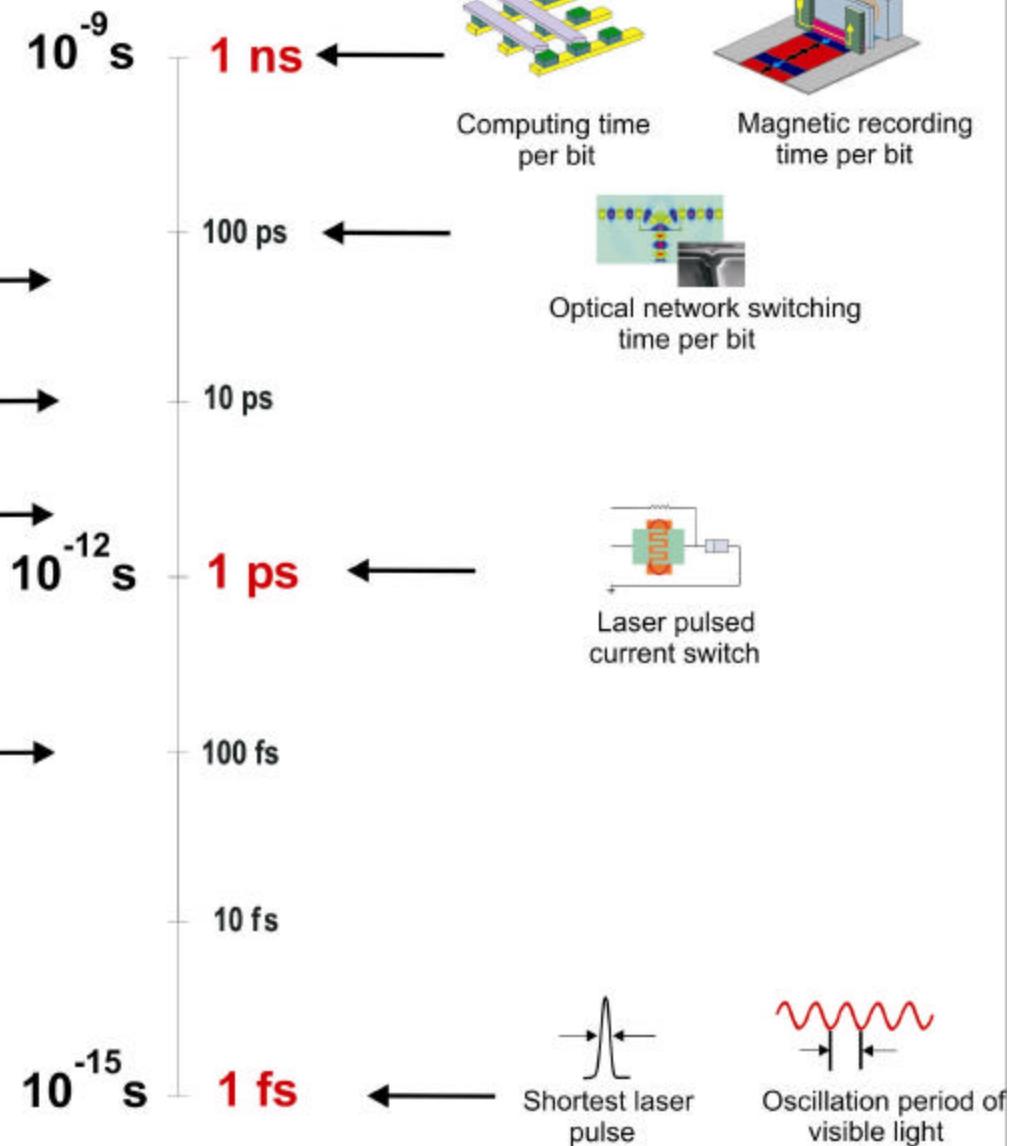
S. Eisebitt, M. Lörgen, J. Lüning, J. Stöhr, W. Eberhardt, E. Fullerton (unpublished)

# X-rays open the Ultra-Small and Ultra-Fast Worlds

## X-Rays and Magnetism



## Technology



# Magnetization and Spin Dynamics

*Magnetism ruled by four fundamental interactions:*

**Exchange interaction** => produces magnetic order on atomic scale,  
magnetic stiffness,  $T_C$ ,  $T_N$ ,  
spin-spin scattering, coherence time of spin excitations

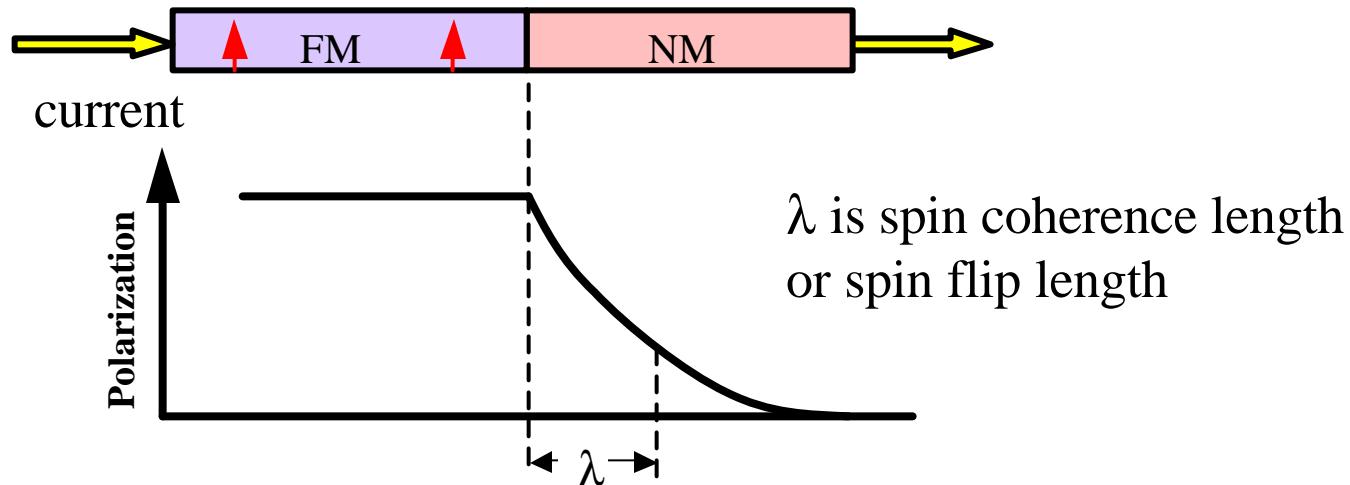
**Spin-orbit interaction** => produces magneto-crystalline anisotropy,  
spin-phonon (thermal) excitations,  
friction (**Gilbert damping**)

**Zeeman interaction** => produces macroscopic spin alignment,  
torque (**Landau-Lifshitz**), magnetic switching

**Dipolar interaction** => produces shape anisotropy,  
magnetic domain structure and motion

	Energy/atom	time scale	length scale
Exchange	eV	fs	atomic
Spin-orbit	meV- meV	ps - ns	nano (nm)
Zeeman	< meV	ps - ns	> nano
Dipolar	< meV	ps - ms	> nano

## Spin injection



$\lambda \sim 1 \text{ nm}$  for ferromagnets (or 10 fs)

$\lambda \sim 1 \mu\text{m}$  for noble metals (or 10 ps)

$\lambda \sim 100 \mu\text{m}$  for semiconductors (or 1 ns)

X-ray experiments can observe:  
effect, size, sign and dynamics